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A DIRECT VOLTAGE CONVERTER WITHOUT TRANSFORMER

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16. Abstract The paper describes the operating principle of a direct voltage converter without a transformer and presents an analysis together with an example of a circuit. The converter can be applied to supply electronic devices operating at low and high power consumption. The converter has a high power efficiency. Because the converter operates without a transformer, it can be designed using IC technology.

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A DIRECT VOLTAGE CONVERTER WITHOUT TRANSFORMER

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Various designs of dc-dc converters with a varying supply voltage are known in the technical literature and in practical applications. /23*

A common feature of known converters, regardless of the system used, is that the dc voltage from the supply source is transformed into an ac voltage. The dc voltage obtained is increased or decreased using a transformer with an appropriately selected current ratio. The voltage is then rectified and filtered. The magnetic flux passing through the transformer windings transfers the energy from the supply source to the load.

The necessity of using a transformer makes miniaturization of the converter much more difficult, and it cannot be designed as an integrated circuit.

This paper describes a capacitor-switch converter in which the capacitor charged from the supply source and discharged into the load circuit transfers the energy. The capacitor is charged and discharged periodically with a frequency determined by an appropriate electronic system.

Operating Principle of the Converter

The principle on which the single-throw converter which doubles the voltage operates is illustrated in Fig. 1. During the charging, capacitor C is connected in parallel to the supply

* Numbers in the margin indicate pagination in the foreign text.

battery, and it is charged to the voltage $u_c \approx U_B$. When it is discharged, the capacitor is connected in parallel to the supply source. In this situation the voltage

$$u_o = U_B + u_c \approx 2U_B$$ /24

is applied to load R_o.

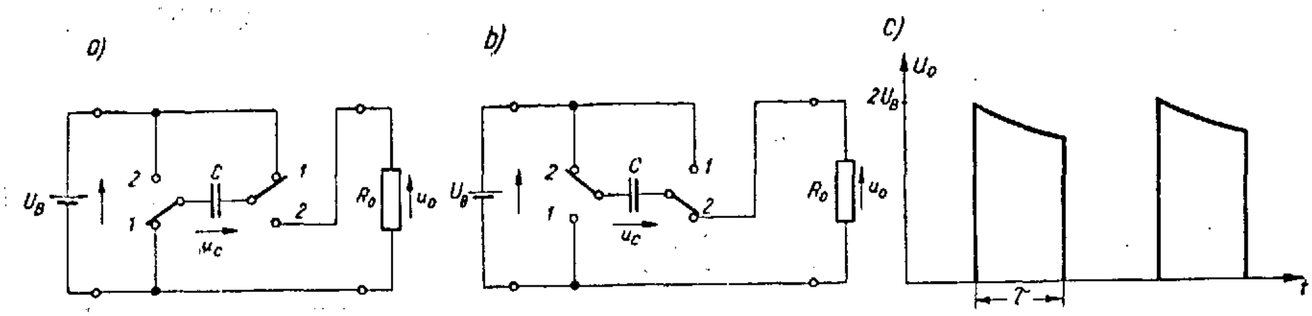

Fig. 1. Operating principle of single-throw converter doubling the voltage: a) charging; b) discharging; c) voltage across load.

As a result of discharging the capacitor, the voltage across the load decreases exponentially. After a definite time period, the capacitor must again be serially connected to the source to equalize the charge. When the capacitor is charged periodically, the voltage curve across the load shown in Fig. 1c is obtained in the system under consideration.

To fill the interval between successive voltage pulses u_o, the double-throw converter system shown in Fig. 2a can be used. This system includes two capacitors C_1 and C_2 together with appropriate switches. The switches are connected and synchronized in such a way that when capacitor C_1 is charged, capacitor C_2 is discharged in the load circuit R_o and vice-versa.

The voltage across the load in the double-throw converter is shown in Fig. 2b. At the moments when capacitors C_1 and C_2 are switched, the voltage across the load drops to zero. This can

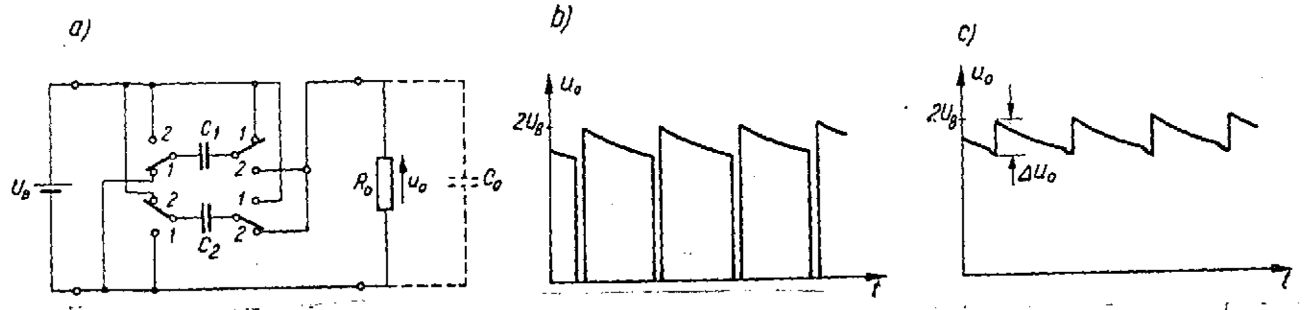

Fig. 2. a) Double-throw converter system; b) output voltage; c) output voltage after capacitor C_o has been connected.

be avoided by connecting serially to the load capacitor C_o, as indicated in Fig. 2 by the dashed line. In this system, the charge accumulated in capacitor C_o will maintain the voltage at the converter output at the switching moments, and the voltage curve u_o obtained is shown in Fig. 2c.

For an appropriately selected switching frequency and a large capacitance of the capacitors used, the variable-voltage component Δu_o at the output (Fig. 2) will be sufficiently small. When necessary, an additional low-pass filter can be used at the output besides capacitor C_o.

In the double-throw converter system discussed (Fig. 2), in each half-period the supply battery equalizes the charge in one capacitor and, at the same time, supplies a serially connected charge to the other capacitor. From here it is evident that the battery is charged by a current which is twice as high as the current flow in the load, whereas the voltage across the load is twice as high as the supply voltage. When there is no charge, $R_o \to \infty$, both capacitors are charged to U_B volts, and the current drawn from the battery drops to zero. When the load resistance is reduced, the battery current increases correspondingly. It is evident from the discussions presented above that the capacitor-switch converter under consideration behaves like a 1:2 dc step-up transformer. When n converter stages are connected, the output voltage is $U_B \cdot 2^n$ (Fig. 3). Other output voltage values, for example, $3U_B$, $6U_B$, $7U_B$, etc., can be obtained between the stages of such a circuit.

A doubling of the dc voltage is also obtained in the system shown in Fig. 4. The operating principle is the same as in the system shown in Fig. 2a. The supply source which is switched periodically with the frequency determined, alternately charges capacitors C_1 and C_2 to voltage U_B. The serially connected capacitors supply load R_o with the voltage $2U_B$. A possible short-coming is that the supply source is not connected electrically to the load; hence, it is not possible to ground simultaneously the source U_B and the load R_o.

The converter system (Fig. 4) can be built using n serially connected capacitors (Fig. 5). The selector switch, which is switched with a particular frequency, charges sequentially all capacitors $C_1 \ldots C_n$ to the voltage U_B. The sum of the voltages nU_B appears across load R_o. The switching frequency and the capacitance of the capacitors used must be sufficiently high, so that the voltage changes on the capacitors during the full charging cycle resulting from the discharge due to the charging are negligibly small.

When the supply source U_B and load R_o are replaced at points in the systems shown in Figs. 4 and 5, we obtain a converter which reduces the dc voltage twice (Fig. 6a) and n times (Fig. 6b). Such a converter behaves like a 2:1 or n:1 step-down transformer.

The watt-hour efficiency of the capacitor-switch converter can be very high if the capacitors are good charge retainers. The /25
only reason for power losses are the series-connected resistors of the switches and capacitors. In the actual design of the converter, these losses should not play an important role.

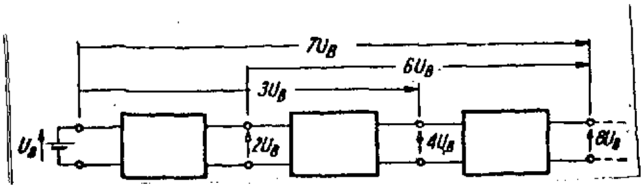

Fig. 3. Cascade connection of converters doubling the voltage.

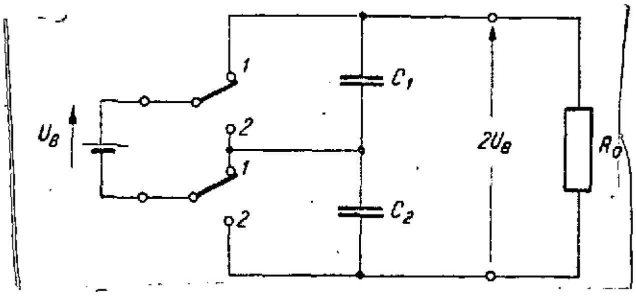

Fig. 4. Different design of doubling voltage converter.

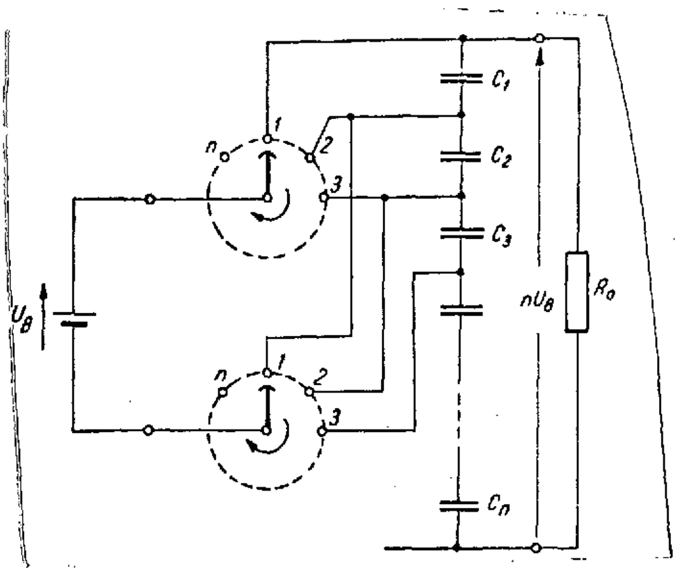

Fig. 5. Capacitor-switch converter increasing dc voltage n times.

Example of Construction and Analysis of System

The converter systems discussed can be designed using mechanical vibratory switches with an appropriate frequency, for example, contactor switches. However, electronically switched systems ensuring higher operating reliability may be used in practice.

An example of a completed converter (Fig. 2) using electronic switches is shown in Fig. 7. The given system operates on the following principle:

A monostable symmetric multivibrator supplies the transistor bases T_1-T_4 in such a manner that in the first half-period transistors T_1 and T_4 are highly conductive and in the saturation state, whereas transistors T_2 and T_3 are blocked. In the next half-period transistors T_1 and T_4 remain blocked, whereas transistors T_2 and T_3 are highly conductive.

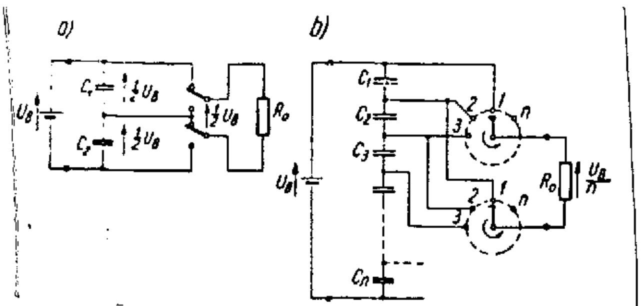

Fig. 6. Converter reducing voltage: a) twice; b) n times.

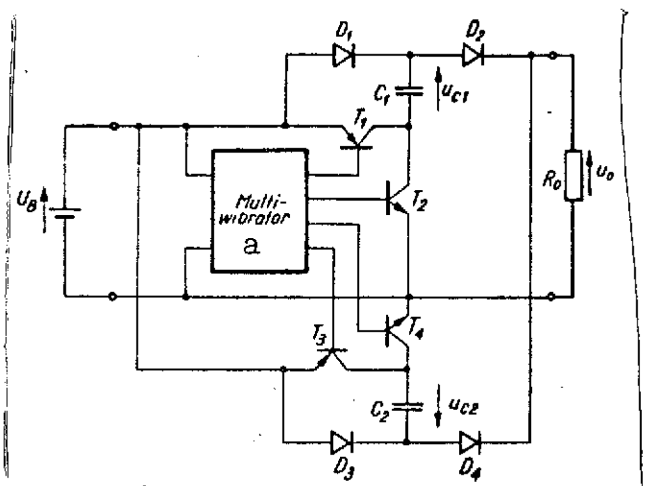

Fig. 7. Converter according to Fig. 2a using transistorized diode switches.

Key: a. Multivibrator.

The voltage drop across the conducting transistors is very small. In the first half-period, due to the small voltage drop in transistor T_1, capacitor C_1 remains serially connected to the supply source, and it is discharged through diode D_2 and load R_o. A voltage which is equal to the sum of the supply voltage U_B and the voltage u_{c1} is applied to the load. At the same time, capacitor C_2 is charged through diode D_3 and the conductive transistor T_4 to a voltage $u_{c2} \approx U_B$. After the multivibrator is switched, capacitor C_1 makes the transition to the charging state through diode D_1 and transistor T_2, whereas transistor C_2, charged earlier, is discharged serially with the supply source U_B voltage through diode D_4 and load R_o.

The purpose of the analysis presented below is to explain the effect of the switching frequency and the capacitance on the operating conditions and efficiency of the converter shown in Fig. 7.

Let us first consider the discharging cycle. The equivalent circuit taken from the system represented in Fig. 8 is shown in

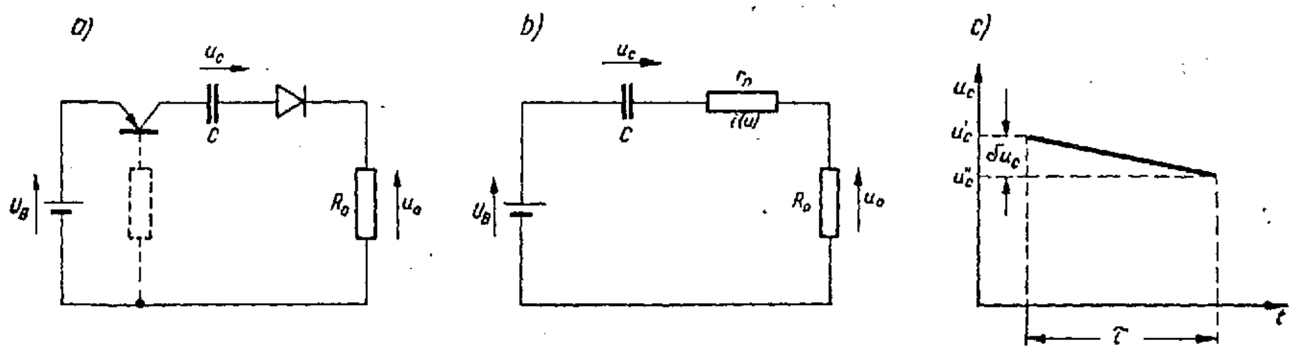

Fig. 8. Discharging cycle: a) element in discharging circuit; b) transistor and diode replaced by nonlinear element r_n; c) voltage across capacitor

Fig. 8a. The highly conductive transistor and the diode can be replaced by a single nonlinear element with the characteristic i(u), obtained by adding the characteristics of the individual elements (Fig. 8b). The voltage curve u_c during the discharge is shown in Fig. 8c.

If we impose the condition that the change in voltage across the capacitor during the discharging cycle be small $\delta u_c \ll U_B$, we can assume the current in load R_0 to be practically constant, so that

$$\delta u_c = i\,\tau / C \qquad (1)$$

where τ is the duration of the discharging cycle.

In the discharging cycle the voltage across the capacitor is reduced from the initial value u_c' to the value u_c'':

$$u_c'' = u_c' - \delta u_c \qquad (2)$$

We will now discuss the charging cycle. The circuit activated in the charging cycle is shown in Fig. 9a. The voltage u_c across the capacitor increases from the value u_c'' to the value u_c', with

$$u_0' = U_B - \gamma u \qquad (3)$$

where γ_u denotes the voltage loss occurring due to the incomplete charging of the capacitor through the nonlinear element r_n. We will apply the intermediate method illustrated in Fig. 10.

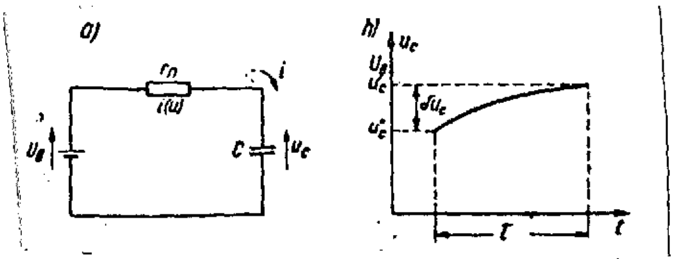

Fig. 9. Charging cycle:
a) charging circuit; b) voltage across capacitor.

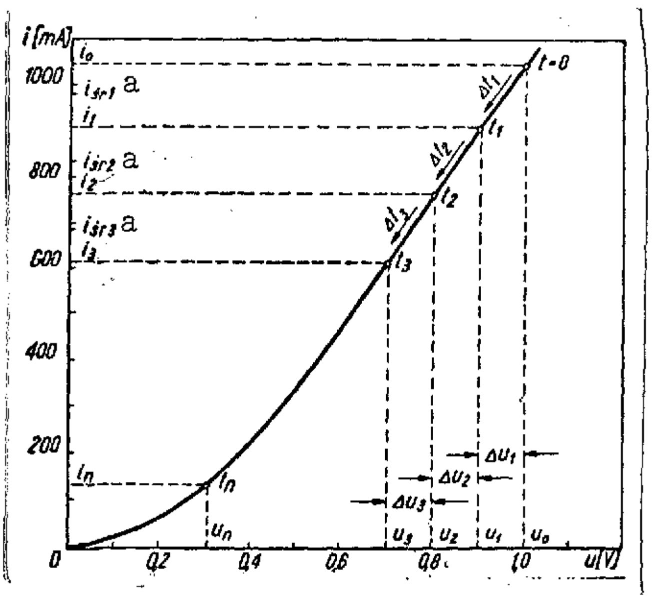

Fig. 10. Illustration for calculation of capacitor charging curve across nonlinear element r_n.

Key: a. i_{mean} ...

The figure discussed shows the characteristic $i(u)$ of the nonlinear element r_n. In the case under consideration, it is the resulting characteristic of diode DMG5, serially connected to transistor BUY54, if the transistor base current is 20 mA. Let us assume that at a selected moment of time, which we denote arbitrarily by t = 0, the voltage $u_o = U_B - u_c$ is applied to the system shown in Fig. 9a. Let us determine the time Δt after which the voltage across r_n decreases by the value Δu_1.

$$\Delta u_1 = \frac{i_{mean\,1}\,\Delta t_1}{C} \qquad i_{mean\,1} = \frac{i_o + i_1}{2}$$

From the above

$$\frac{\Delta t_1}{C} = \frac{\Delta u_1}{i_{mean\,1}} \qquad (4)$$

Dividing the time interval Δt by the capacitance C, we obtain the normalized time, which is independent of the values given. /26

Using expression (4) and the values determined in Fig. 10, we can calculate the next time interval Δt_2 in which the voltage across r_n changes from u_1 to u_2:

$$\frac{\Delta t_2}{C} = \frac{\Delta u_2}{i_{mean\ 2}} .$$

The time t_n corresponding to a change in the voltage from u_o to u_n can be calculated in this manner:

$$\frac{t_n}{C} = \sum_{i=1}^{n} \frac{\Delta t_i}{C} = \sum_{i=1}^{n} \frac{\Delta u_i}{i_{mean}} \quad (5)$$

Making the calculations for different values of n, we obtain the relationship sought between the change in the voltage at the nonlinear element and the time which elapsed since the switching moment, i.e., since the moment at which the charging cycle began. This relationship is calculated on the basis of the graph of i(u) shown in Fig. 10, and it is plotted in Fig. 11. The scale t/C is linear. The graph of u(t/C) can also be extended to the left of the point t = 0, where the initial point u_o on the characteristic i(u) was taken arbitrarily.

The curve in Fig. 11 gives the values of the current flowing through the nonlinear element under consideration, which correspond to the values of the voltage read off on the ordinate.

We will now discuss the use of the graph obtained.

For designing the converter system, we must start out with the required value of the current i drawn through the load and use the admissible value for the change in voltage δu_c in the charging cycle (Fig. 8c). From expression (1) we obtain:

$$\frac{\tau}{C} = \frac{\delta u_c}{i} \tag{6}$$

The value of τ/C calculated from the above can be determined by taking C as the value of the capacitance and by selecting the switching frequency (τ is the switching half-period).

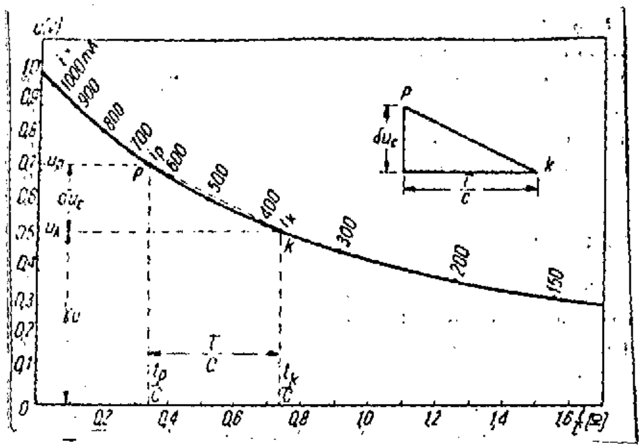

Fig. 11. Auxiliary nonlinear capacitor charging curve (graphic construction explained in text).

Using the graph plotted in Fig. 11, we can determine the range for the variation in the voltage at the nonlinear element r_n during the charging cycle and the range for the variation in the charging current. To this end, we must find on curve u(t/C) two points p and k denoting the beginning and end of the charging cycle whose coordinates satisfy the following conditions:

$$\left.\begin{aligned} u_p - u_k &= \delta u_c \\ \frac{t_k}{C} - \frac{t_p}{C} &= \frac{\tau}{C} \end{aligned}\right| \tag{7}$$

We can use an auxiliary drawing, i.e., a right-angled triangle whose vertical leg is equal to the assumed value of δu_c and whose horizontal leg is equal to the calculated value of τ/C. The auxiliary triangle drawn on tracing paper is superimposed on the drawing and displaced parallel to it until the vertices p and k of the triangle intersect the curve as indicated in Fig. 11 by the dashed lines.

Next, the values of the initial current i_p, of the final current i_k and the voltage loss γu can be calculated. The mean voltage across the capacitor during the discharging cycle will be calculated from the expression

$$u_{c\,\mathrm{mean}} = U_B - \gamma u - \frac{1}{2}\delta u_c \qquad (8)$$

The mean voltage across the load is (Fig. 8): /27

$$u_o = 2U_B - \gamma u - \frac{1}{2}\delta u_c - u(i) \qquad (9)$$

In this expression u(i) is the voltage drop across the nonlinear element r_n occurring in the discharging circuit.

For a constant ratio τ/C, a current increase in the load results in an increase in δu_c. The vertical leg of the auxiliary right-angled triangle becomes longer, and the triangle is displaced along the curve to the left, i.e., in the directionoof higher currents. The voltage loss τu increases, and the mean voltage across the load determined from expression (9) decreases. Making similar calculations for two different values of the current in the load and determining the change in the mean voltage across the loads, the internal resistance of the converter can be determined.

For a direct current in the load, a decrease in the ratio τ/C brings about a proportional decrease in the component δu_c. The inclination of the hypotenuse of the auxiliary triangle does not change. At the limit, as $\tau/C \to 0$, $\delta u_c \to 0$. The vertices p and k of the triangle converge to a single point in the drawing, at which the hypotenuse of the auxiliary triangle becomes the tangent to the curve. The current flowing at this time through the nonlinear element during the charging cycle is nearly constant and equal to the current drawn through the load.

In the double-throw converter shown in Fig. 7, the supply source U_B supplies at each instant the current directly to the load R_0 connected serially to the discharged capacitor (Fig. 8a,b) and at the same time supplies the circuit of the second capacitor which is in the charging state (Fig. 9a). The currents in both branches are nearly equal.

The power generated in the load is $P_0 = u_0 i$, and the power from the supply source is $P_S = 2U_B i$. The watt=hour efficiency of the converter can be described by the formula

$$\eta = \frac{P_o}{P_S} = 1 - \frac{\gamma u + \frac{1}{2}\delta u_c + u(i)}{2U_B} \tag{10}$$

Assuming for the sake of simplicity that $\delta u_c = 0$ and $\gamma u = u(i)$, we obtain

$$\eta = 1 - \frac{u(i)}{U_B} \tag{11}$$

After the condition $\tau/\theta \to 0$ is satisfied, to obtain high efficiency, diodes and transistors with minimal voltage drop for a given current must be used. In this respect, germanium diodes are undoubtedly superior to silicon diodes. The transistor base current must be sufficient to ensure operation in the saturation state, even when the maximum current flows through the transistor.

To calculate efficiency, the power drawn by the keying multivibrator and by the transistor base circuits must be taken into account. If the system is designed carefully and transistors with a high value of h_{21} are used, the drop in efficiency should not exceed several percent.

Numerical Example

To illustrate the discussion, let us design a converter which doubles the voltage and operates in the system shown in Fig. 7.

The initial data for the design are:

-- supply voltage U_B = 12 V

-- initial voltage $u_o \approx 24$ V

-- charging current i = 0.5 A

-- permissible voltage changes $\delta u_c \leq 0.2$ V.

We will use DMG5 diodes and BUY54 transistors. The resulting characteristic of the nonlinear element r_n during the charging cycle is shown in Fig. 10. The auxiliary characteristic calculated on the basis of this graph is shown in Fig. 11.

From Eq. (6) we calculate

$$\frac{\tau}{C} = \frac{0.2\ \text{V}}{0.5\ \text{A}} = 0.4\ \Omega$$

Let us make capacitance C = 1000 μF/12 V and calculate the corresponding required switching frequency

$$f_p = 1/2\tau = 1.25\ \text{kHz}.$$

Using the auxiliary drawing shown in Fig. 11, we contruct a right-angled triangle with the legs $\delta u_c = 0.2$ V, $\tau/C = 0.4\ \Omega$ and shift it so that the vertices p and k lie on the curve $u(t/C)$. Using the graph constructed we obtain the following numerical values:

$u_p = 0.82$ V $\qquad u_k = \gamma u = 0.52$ V

$i_p = 640$ mA $\qquad i_k = 370$ mA.

The voltage drop across the nonlinear element for a current /28
$i = 500$ mA is $u(i) = 0.62$ V. The mean voltage across the load

will be, according to Eq. (9):

$$u_o = 24 - 0.52 - 0.1 - 0.62 = 22.76V$$

The power output generated in the load is:

$$P_o = 22.76\ V \cdot 0.5\ A = 11.38\ W$$

The watt-hour efficiency calculated from Eq. (11) is

$$\eta = \left(1 - \frac{0.62}{12}\right) \cdot 100\% = 94.8\%$$

The power loss P_b in the circuits of the two active transistor bases with the assumed base current i_b = 20 mA is

$$P_b = 2U_B \cdot i_b = 24\ V \cdot 20\ mA = 480\ mW$$

Let us assume for preliminary orientation purposes that the power drawn by the control multivibrator is

$$P_m = 12\ V \cdot 5\ mA = 67\ mW$$

After the additional power drawn by the base circuits and the multivibrator is taken into account, we obtain the resulting efficiency of the converter

$$\eta_{res} = 90\%$$

It is evident from the example presented that the converter system under consideration has a high watt-hour efficiency, which is better than the efficiency of conventional transistorized converters with a transformer.

The practical systems built confirmed the possibility of using dc voltage converters without a transformer for the supply of low-power and high-power equipment using dc power ranging from several millivolts to several hundred watts.